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Layer depth constrained servo scanning EDM for 3D microstructures

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Abstract

Servo scanning 3D micro electro discharge machining (3D SSMEDM) method can automatically compensate the axial wear of micro rod-electrode in real time by preferably keeping a discharge gap. However, the depth errors of 3D SSMEDM were even to 10% due to the accumulation of layers' thickness errors. In addition, the machining process with keeping the discharge gap must bring the initial errors of inclined or uneven workpiece-surfaces into dimensional errors, and also cause that 3D structures cannot be machined on the workpieces with a hollow area. In this study, a layer depth constrained algorithm (LDCA) is proposed to solve the above problems. LDCA strategy is to control an electrode-feed maximum at every scanning spot during 3D SSMEDM processes. By using LDCA, machining experiments were carried out on several typical micro cavities <1mm of rectangle, truncated cone and cross structure. The experimental results show: The accumulation errors of the layers' thickness can be avoided, so the machined depth errors can be controlled <2μm. The designed 3D structures can be machined in the workpieces with unknown hollow areas.

Keywords: micro EDM milling; servo scanning machining; 3D micro structure; electrode wear; layer thickness algorithm

1. Introduction

Advanced machining technologies of 3D microstructures are widely valued by researchers. Micro electro discharge machining (EDM) is capable of forming complex 3D microstructures by a rod-like tool electrode to scan layer-by-layer. The scanning 3D micro EDM has the special advantages of low setup cost, design freedom and easy removal of chips.

During micro EDM, the interelectrode distribution of discharge energy determines the inevitability of tool-electrode wear. Compensation technologies of electrode wear is a key for an available process of 3D scanning micro EDM [1-2]. Based on digital imaging, experimental models and intermittent feed [3-5], the usual compensation methods are difficult to achieve high discharge rate due to the poor real-time performance of the compensation processes.

In our previous study, a servo scanning 3D micro EDM (3D SSMEDM) was proposed to compensate the axial wear of micro electrode in real time by preferably keeping a discharge gap [6-8]. The discharge gap is kept by servo controlling tool-electrode to feed or withdraw in the axial direction based on the comparison between the feedback of interelectrode electric signal with the given value of well-discharge state.

The principle of 3D SSMEDM is illustrated as follows. Given electrical parameters as constants, the discharge energy of single-spark is W_M, and the certain range S_B of suitable discharge gap belongs to [S_{min}, S_{max}]. If interelectrode gap is kept in [S_{min}, S_{max}], the discharge times in per-unit time T_u (discharge frequency f_e) would be a statistical constant. Thus, the discharge energy in T_u is as $W_T= W_M*f_e$, and the removed material volume in T_u is a statistical constant as $V_T=k_a*W_T$ with a factor k_a. If set scanning speed v_s and electrode diameter d_s, the machined depth h_T with keeping the discharge gap S_B should be Eq.(1):

$$h_T = \frac{V_T}{v_s d_s} = \frac{k_a W_M f_e}{v_s d_s} \qquad (1)$$

According to Eq.(1), the machined depth h_T is a statistical constant. Setting the depth constant as laminated thickness, the 3D micro cavities can be formed according to the planed scanning paths. The depth constant is obtained by a basic experiment under the conditions of the given machining parameters.

The specific advantage of 3D SSMEDM lies in the electrode-wear compensation without measuring the

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wear value. The axial wear of tool-electrode can be automatically compensated only by servo control of discharge gap, which brings the advantage of high machining efficiency.

However, the depth accuracy of micro cavity is hardly guaranteed by the overlay of multi-layers' thickness, because the actual depth is without feedback during machining process. Essentially, 3D SSMEDM is a contour process followed by the workpiece-surface shape if a discharge gap is kept in real time. The contour process must bring the initial errors of inclined or uneven workpiece into dimensional errors, and the errors are accumulated layer by layer. The accumulated errors also come from the changes of scanning path, discharge state and dielectric flow. Our experiments showed the depth errors were even up to 10%, which cannot meet the accuracy requirements of micro-structures. Besides, 3D structures cannot be machined in the zones with a hollow area due to the contour process.

In this study, a layer depth constrained algorithm (LDCA) is proposed to solve the above problems. LDCA is to ensure layer-thickness consistent without regarding of the workpiece surface morphology. LDCA strategy is to control the electrode feed reaching the calculated electrode-feed maximum while keeping discharge gap. Both high processing efficiency and precise machined depth are desired to be achieved.

2. Precision control principle of LDCA

The principle of the proposed LDCA is illustrated in Fig.1. Suppose the workpiece surface to be machined is flat and uniform, we set the constants including laminated thickness of h, scanning speed of v_s and electrode diameter of d_s, and set the variables including servo-scanning path length of x and its electrode-wear length of Δl_x. The electrode-feed depth at every scanning point within the scanning layer should be $h+\Delta l_x$. It is the common knowledge that wear volume of tool electrode is proportional to the removed volume of workpiece material, namely

$$\pi(d_s/2)^2\Delta l_x = k_b(d_s hx) \qquad (2)$$

where k_b is a coefficient constant.

Then, Eq. (2) can be transformed into Eq. (3), and electrode-wear length of Δl_x can be gained as:

$$\Delta l_x = (\frac{4k_b}{\pi})(\frac{h}{d_s})x \qquad (3)$$

Thus, after path length x is servo scanned, electrode-feed depth Z_x can be calculated as Eq. (4):

$$\mathrm{Z_x} = h + \Delta l_x = h + (\frac{4k_b}{\pi})(\frac{h}{d_s})x \qquad (4)$$

According to Eq. (4), we define a wear coefficient K_x showed in Eq.(5) as the electrode-wear length after the path length of per-unit is scanned by keeping discharge gap.

$$K_{\mathrm{x}} = (\frac{4k_b}{\pi})(\frac{h}{d_s}) \qquad (5)$$

From Eq.(5), we can draw a conclusion that K_x is a constant only if machining conditions are given.

Using the above principle, the layer depth constrained algorithm (LDCA) is proposed to control an electrode-feed maximum at every scanning spot during 3D SSMEDM processes. LDCA requires the following constraints:

(1) The electrode-feed maximum at every scanning spot is calculated by Eq.(6):

$$\mathrm{Z_{max}} = h + \Delta l_{\sum x} = h + K_{\mathrm{x}}\sum x_i \qquad (6)$$

where x_i means the servo-scanning path length by servo controlling a discharge gap in real time.

(2) When electrode feed depth h_{Feed} reaches electrode-feed maximum $Z_{\max}$ at every scanning spot, the servo control of discharge gap is paused and pulsed power supply is powered off. At the same time, the low voltage sensing circuit between electrode and workpiece is opened. Then, tool-electrode goes on scanning until interelectrode short-circuit occurs. When short circuit occurs, the servo control of discharge gap is restarted and the pulsed power supply is powered on again.

(3) During the paused process of the servo control, the scanning-path length (Non-machining path) is excluded from $\sum x_i$.

From the (1)-(3) constraints, $\sum x_i$ fits for the continuous conditions (Eq.5) of the 3D-SSMEDM process shown in Fig.1. Therefore, the electrode-feed maximum at every scanning spot can be calculated if the wear coefficient K_x and the sum of servo-scanning path length are known during 3D-SSMEDM.

For an example shown in the fig.2, although the surface is uneven, the machined depth can be controlled to the dependent parameter h (laminated thickness) by LDCA. Overcutting can be adaptively avoided with the servo of full-time or intermittent or no-time. Thus, microstructures can be machined on an unknown hollow area.

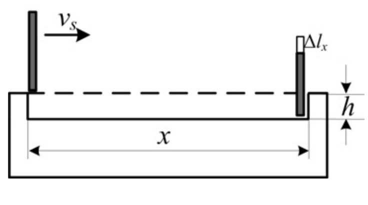


Fig.1. Electrode wear Δl_x after servo-scanning-path x in 3D-SSMEDM with ideal machined surface

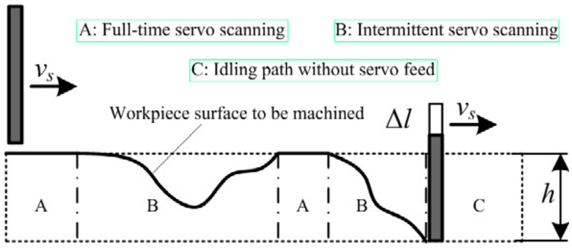


Fig.2. Supposed uneven surface with dependent parameter as laminated thickness h

3. Implementation process of LDCA

The 3D SSMEDM process with LDCA is shown in Fig.3. First, 3D model is designed by Pro/Engineer, and machining parameters are set including electrical parameters, electrode size, scanning speed, etc. Using the set machining parameters, a basic machining experiment of 3D SSMEDM without LDCA is carried out to obtain the key parameters of laminated thickness and wear coefficient K_x. The laminated thickness for LDCA should be slightly smaller than the machined depth each layer by 3D SSMEDM without LDCA, because the depth is a maximum by adopting the full-time servo process. According to the laminated thickness, 3D numerical control (NC) codes are generated by CAM software [9]. At last, the 3D micro-cavities would be formed.

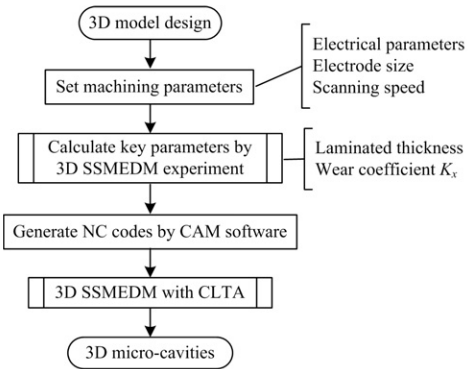


Fig.3. Implementation process of 3D SSMEDM with LDCA

From the LDCA principle, the LDCA implementation requires real-time computer control. The control software process is shown in Fig. 4. Multi-segments of servo-scanning path length are summed and electrode-feed maximum of scanning spot is calculated as soon as the control program starts. Then, the relation between electrode-feed depth h_{Feed} and electrode-feed maximum $Z_{\max}$ is judged. If $h_{\mathrm{Feed}}>Z_{\max}$ indicating that tool-electrode end reaches the controlled depth of scanning layer, the servo feed of tool electrode pauses and the inter-electrode voltage switches into low value of 24V. Then, the scanning process goes on according to 3D NC codes with keeping electrode position. When interelectrode short circuit is monitored, servo control of discharge gap (servo feed of tool electrode) is re-activated. The short circuit indicates the depth of scanning point does not reach the controlled depth. The process is repeated for every scanning point of all layers until NC-codes of all paths are finished.

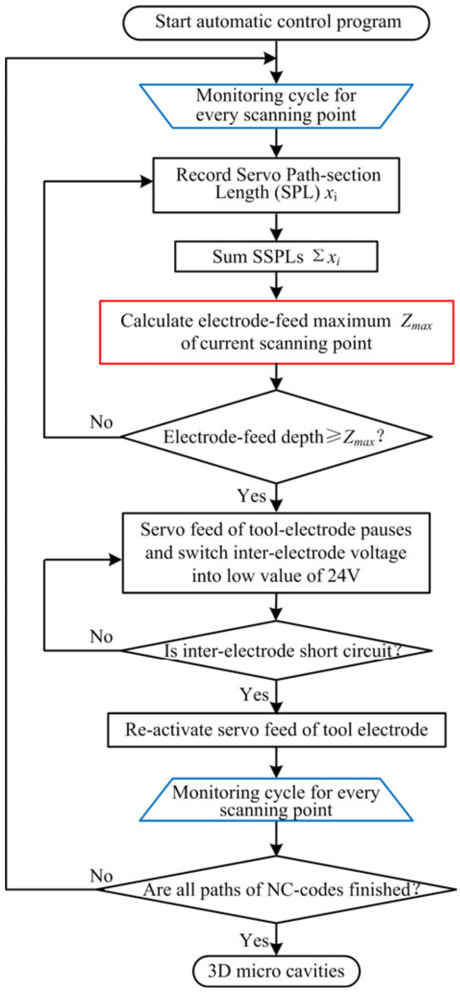


Fig.4. Software process of LDCA

4. Machining experiments for verifying LDCA

To verify LDCA, machining experiments were carried out on several micro cavities <1mm. The shapes and dimensions of micro cavities are measured by their injected molds [10]. The machining parameters are presented in Table 1.

Fig.5 shows the configuration of experimental setup, which consists mainly of an XY worktable, a micro-feed mechanism (Z axis) for servo control of discharge gap, a wire electric discharge grinding (WEDG) mechanism for fabricating micro electrode [11], and a pulsed power supply. The positioning resolution of the XY worktable is ±2μm. The micro-feed mechanism possesses a moving resolution of 0.3μm and a response frequency of 63Hz. The minimum pulse width of the pulse power supply is 1μs.

Table 1. Experimental parameters

Parameters	Value
Open voltage (*V*)	110
Pulse duration (*μs*)	3
Pulse interval (*μs*)	5
Discharge capacitor (*pF*)	1000
Material of tool electrode	Tungsten
Size of tool electrode (*μm*)	*Φ*80
Material of workpiece	Copper sheet
Dielectric fluid	Oil
Scanning speed (*mm/s*)	0.2
Track overlapping (*μm*)	30
Laminated thickness without LDCA (*μm*)	1.65
Laminated thickness with LDCA (*μm*)	1.2 or 1.0
Wear coefficient of K_x	0.0011

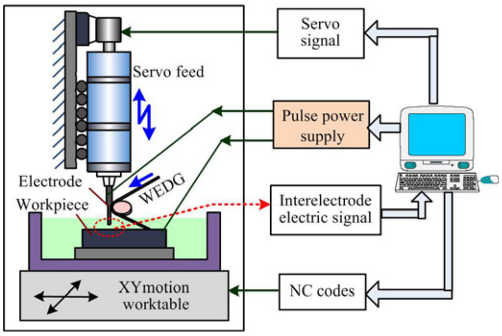
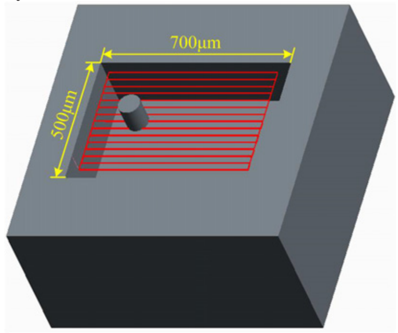


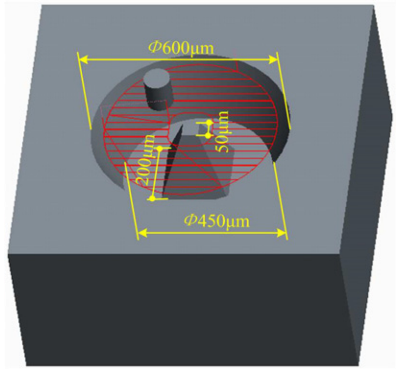
Fig.5 Configuration of experimental setup

By using 3D software of Pro/Engineering, the models were designed and scanning paths were planned for the micro cavities, as shown in Fig.6. The designed dimensions are less than 800μm. For the cross-structure cavity (Fig.6c), the deep groove marked as A region (depth 80μm) is machined before the groove marked as B region (depth 60μm). The A region can provide a hollow area for the B region on the workpiece.

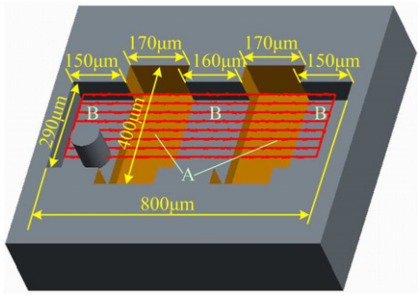
By machining the micro rectangle cavities (Fig.6a), the contrast curves between with LDCA and without LDCA are shown Fig.7. Although the machining efficiency with LDCA is slightly lower than that without LDCA, the consistency accuracy of machined layer depth with LDCA is obviously better than that without LDCA. With the increase of machined depth and layers, the layer depth can be precisely controlled by LDCA. Without using LDCA, the depth errors are accumulated layer by layer.



(a) Rectangle;



(b) Truncated cone;



(c) Cross structure;

Fig.6 Model design and path scanning of micro cavities

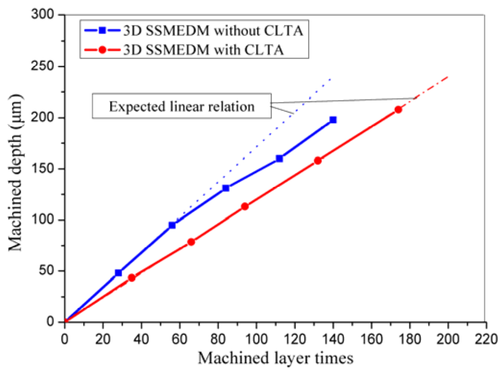
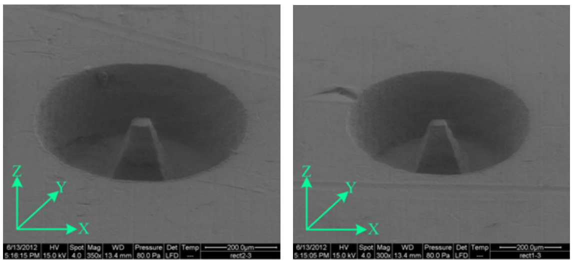
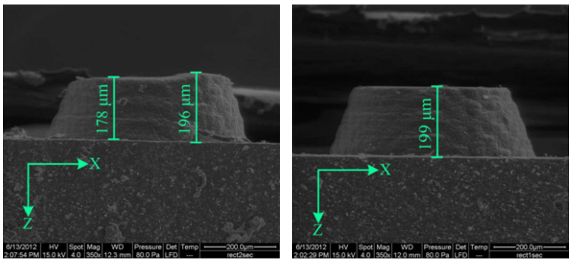


Fig.7. Relation curves between machined layer times and depths

The machined results of the truncated cones are compared in Fig.8 under the conditions with LDCA and without LDCA respectively. From the scanning electron microscope (SEM) photographs, the dimensional accuracies in the direction of XY are basically same regardless of whether using LDCA. The accuracies of depth and surface integrity are clearly different between without LDCA and with LDCA. Without LDCA, the depth errors in the direction of Z are larger even up to 12μm, and the bottom surface is uneven. With LDCA, the depth error can be precisely controlled <2μm, and the bottom surface is flat.



(a) Micro cavity (without LDCA); (b) Micro cavity (With LDCA);



(c) Injected mold (without LDCA); (d) Injected mold (with LDCA);

Fig.8. SEM photographs of truncated-cone micro cavities

By 3D SSMEDM with LDCA, the machined cavity of cross structure is shown in Fig.9. The experimental result shows that the designed structure can be successfully machined on the workpiece with the hollow area. Seen from Fig.9(b) and (c), the dimensional accuracy is free from the hollow area, and the depth error can be controlled <2μm. The corner errors mainly come from the corner wear of tool electrode during the scanning process.

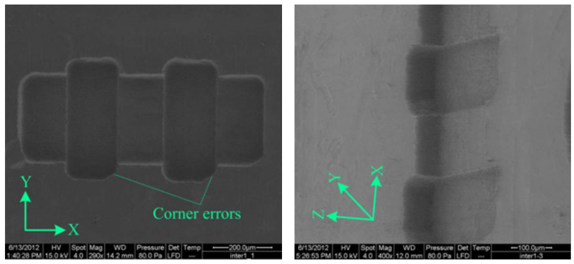
5. Conclusions

To avoid surface-flatness errors and depth-errors in 3D SSMEDM, the layer depth constrained algorithm (LDCA) has been proposed and applied. By LDCA, the high-precision uniformity of scanning layers can be realized by controlling the electrode-feed maximums at scanning spots. The machining experiments were carried out on the typical micro cavities (<1mm) of rectangle, truncated cone and cross groove. The conclusions can be drawn as follows:

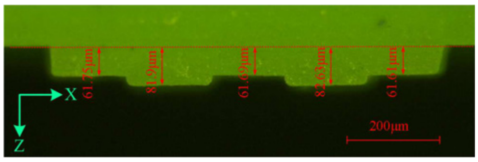
(1) For machining micro-cavities without LDCA, the accumulated errors of layers' thickness cause uneven surfaces and depth errors. Under our experimental conditions, the depth error was even up to 12μm when the depth is expected to 200μm.

(2) By use of LDCA, the machined depth of scanning layers can be precisely controlled. The micro cavities <1mm with flat surfaces were successfully fabricated, and the depth errors can be controlled <2μm.

(3) By use of LDCA, the designed cavities can be formed on the workpiece with unknown hollow areas. In addition, the dimensional accuracy (especially for depth accuracy) is free from the hollow structures.



(a) XY view of micro cavity; (b) XYZ view of micro cavity



(c) XZ view of injected mold

Fig.9 Experimental results of micro cavity of cross-structure

Acknowledgements

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